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A METHOD FOR A ROTATING ELECTRIC MACHINE AND A MACHINE FOR CARRYING OUT THE METHOD

The present invention relates to a method for a rotating electric machine for high voltage and such a rotating electric machine.

The present invention relates especially to a rotating electric machine having the type of winding as defined in the preamble of claims 1 and 26 respectively.

In this connection, rotating electric machines comprise synchronous machines, which are mainly used as generators for connection to distribution and transmission networks, referred to as power networks. Synchronous machines are also used as motors, in addition to phase compensation and voltage regulation and then as mechanically idling machines. This technical field also comprises normal asynchronous machines, dual-feed machines, alternating current machines, asynchronous converter cascades, outer pole machines and synchronous flux machines. These machines are intended for use at high voltages, i. e. voltages that mainly exceed 10 kV. A typical operating range for such a rotating machine may be 36 - 800 kV, and preferably 72,5 - 800 kV.

In conventional types of electric rotating machines the stator body is often designed in the form of a welded steel sheet construction. The stator core, also referred to as a steel core, is normally in larger machines formed of so-called electric sheet which is preferably 0,35-0,50 mm thick and divided into stacks. The stator core is provided with radial slots for the winding so as to form radial layers at different radial distances from the air gaps between the stator and the rotor. The term layer refers to layers of winding at different radial distances from the central axis of the stator. A winding turn is formed by that part of the winding, which extends once back and forth through the stator between different layers.

Rotating electric machines have conventionally been designed for voltages in the range of 6 - 30 kV, and 30 kV has normally been considered to be an upper limit. This generally means that a generator must be connected to the power network via a transformer, which steps up the voltage to the level of the power network, i.e. in the range of approximately 130 - 400 kV.

Different attempts have been made during the course of the years to develop especially synchronous machines, and more especially generators, for high

voltages. Such examples may be found among others in; "Electrical World", October 15, 1932, pages 524 - 525, the article; "Water-and-oil-cooled Turbo-generator TVM-300", in J. Elektrotechnika, No.1, 1970, pages 6 - 8, and in the patent publications US 4,429,244 and SU 955 369. However, none of these attempts have been successful or led to any commercially available product.

It has however been shown feasible to use high voltage insulated conductors as stator winding in a rotating electric machine, which have solid insulation and are of a design similar to cables used for transmission of electric power (e. g. so-called XLPE-cables). The voltage of the machine can be increased hereby to such levels that it can be connected directly to the power network without an intermediate transformer. Thus, among other things, the very important advantage of eliminating the conventional transformer is hereby achieved. A rotating electric machine with such a winding is described for instance in the PCT application WO 97/45919. Additional descriptions of the insulated conductor or cable can be found in the PCT applications WO 97/45918, WO 97/45930 and WO 97/45931.

The above-mentioned type of winding, principally corresponding to cables having solid, extruded insulation of a type presently used for power distribution, such as said XLPE-cables or cables having EPR-insulation, comprises an inner conductor composed of one or more strands, an inner semiconductive layer surrounding the conductor, a solid insulation layer surrounding the inner semiconductive layer and an outer semiconductive layer surrounding the insulation layer. Such cables are flexible, which is an essential property in this context since the technology for the device, according to the invention, is based primarily on a winding system in which the winding is formed from conductors, which are bent during assembly. The flexibility of an XLPE-cable normally corresponds to a radius of curvature of approximately 20 cm for a cable 30 mm in diameter, and a radius of curvature of approximately 65 cm for a cable 80 mm in diameter. In the present application the term flexible is used to indicate that the winding is flexible down to a radius of curvature in the order of 4 times the cable diameter, preferably 8 to 12 times the cable diameter.

The winding should be designed so as to retain its properties even when it is bent and subjected to thermal stress during service. In this connection, it is vital that the layers retain their adhesion to each other. The material properties of the layers are decisive here, particularly their resiliency and relative coefficients of

thermal expansion. In an XLPE-cable, for example, the insulation layer consists of cross- linked, low-density polyethylene and the semiconductive layers consist of polyethylene compounded with soot and metal particles. Changes in volume, as a result of temperature fluctuations, are fully accommodated in the form of changes in the radius of the cable and thanks to the comparatively slight difference between the coefficients of thermal expansion of the layers in relation to the resiliency of these materials the radial expansion of the cable can take place without adhesive failures between the layers.

The material combinations stated above are considered by way of example only. Other combinations fulfilling the above-mentioned conditions and the condition of being semiconductive, i. e. having a volume resistivity within the range of 10^{-1} - 10^{6} ohm-cm, such as 1 - 500 ohm-cm, or 10 - 200 ohm-cm for example, naturally fall within the scope of the invention.

The insulating layer can consist, for example, of a solid thermoplastic material such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polybutylene (PB), polymethyl pentene (PMP), cross-linked materials such as cross-linked polyethylene (XLPE), or rubber such as ethylene propylene rubber (EPR) or silicone rubber.

The inner and outer semiconductive layers may be made of the same basic material but compounded with particles of conducting material such as soot or metal powder.

Ethylene-vinyl-acetate copolymers/nitrile rubber, butyl graft polyethylene, ethylene-butyl-acrylate-copolymers and ethylene-ethyl-acrylate copolymers may also constitute suitable polymers for the semiconductive layers.

Even when different types of material are used as a base in the respective layers, it is desirable that their coefficients of thermal expansion are of the same magnitude. This is the case in the above listed combination of materials.

The materials listed above have a relatively good resiliency, with an E-modulus of E < 500 MPa, preferably < 200 MPa. The resiliency is sufficient for any possible minor differences between the coefficients of thermal expansion of the materials in the layers to be accommodated in the radial direction so that no cracks or other damage appear and so that the layers do not loose adhesion to each other. The materials in the layers are elastic, and the adhesion between the layers is at least of the same magnitude as the weakest of the materials.

The conductivity of the two semiconductive layers is sufficient to substantially equalise the potential along each respective layer. The conductivity of the outer semiconductive layer is sufficiently high to enclose the electrical field within the cable, but sufficiently small so as to not give rise to significant losses due to currents induced in the longitudinal direction of the layer.

Thus, each of the two semiconductive layers essentially constitutes one equipotential surface, and the winding constituting these layers substantially confines the electrical field within itself.

However, nothing prevents one or more additional semiconductive layers from being arranged in the insulating layer.

One problem arising with the use of an XLPE-insulated conductor and the like when used as winding is their expansion, because of their relatively high coefficient of thermal expansion, which occurs as a result of heating when operating the machine. The normal operating temperature for a machine of the present type is in the order of 70°C, which is considerably lower than that of conventional machines that have an operating temperature of approx.100-120°C. The difference in temperature between the machine in operation or out of operation, which temperature difference is normally in the order of 50°C but may even be considerably higher if the machine is placed outdoors in a cold climate, causes an XLPE-insulated conductor that is securely fastened within the stator slots when the machine is in operation, to shrink when the operation of the machine is interrupted and the XLPE-insulated conductor can very possibly loose adhesion to the walls of the slot so that it is more or less loosely positioned when the machine is out of operation. This loose conductor creates a problem when the machine starts operating again. The XLPE-insulated conductor and the stator slots are alternatively dimensioned in such a way in relation to each other that the conductor is fastened within the slot even when the machine is out of operation. When the machine consequently starts operating and the temperature starts rising, the XLPE-insulated conductor in the slots expands thermally and risks being damaged in the slots. Special devices for securing and maintaining the XLPE-insulated conductor may be used as another alternative, but which have the disadvantage of being both costly and difficult to install.

The present invention intends to solve the above-mentioned problems, which are caused by differences in temperature and the thermal expansion of the winding.

The problem is solved, according to the present invention as defined in the characterizing part of claim1, by a method where the stator is cooled while during operation to a temperature T1, and where it is heated while out of operation to a temperature T2. A corresponding rotating electric machine solves the problem as defined in the characterizing part of claim 26. The rotating machine thus comprises a device for cooling the stator, while during operation, to a temperature T1, and for heating the stator, while out of operation, to a temperature T2. The advantage achieved hereby is that said temperature differences are reduced, thereby reducing the thermal expansion of the winding. Because the temperature differences are reduced to a high degree in this way or, according to an especially preferred embodiment, are equalised completely, see below, the problems of different thermal expansion between the solid insulation and the layers surrounding the insulation of the insulated electric conductor in use is also eliminated. Reducing the temperature variation in this way, or alternatively equalising the temperature, makes a freer choice of material in the insulated conductor possible. Thus, other conducting materials, having larger temperature coefficients, may be used and materials having different temperature coefficients may be combined in the solid insulation and surrounding layers.

According to an especially advantageous feature, this device comprises at least one cooling and heating system for the stator and one supervision system comprising means which measure the temperature of the stator both during operation and out of operation respectively, and means which control the cooling and heating system such that said temperatures T1, which the stator cools down to when it is in operation, and T2, which the stator heats up to when it is out of operation respectively, are obtained and maintained.

According to an advantageous feature, the temperature T2 is preferably essentially equal to the temperature T1, which means that the temperature of the stator is held essentially constant regardless of whether it is in operation or not.

According to another advantageous feature, the temperature T 2, which the stator is heated up to when it is out of operation, is somewhat lower than the temperature T1, which the stator is cooled down to when it is in operation, where-

by T2 is preferably in the range of 0 - 20^0 C lower than T1, and with advantage in the range of 0 - 10^0 C lower than T1, or in the order of 10 - 15% lower than T1.

The insulation of the XLPE-conductor remains at a constant volume because the temperature is constant or close to constant, which simplifies securing and assembly of the winding in addition to simplifying and making the whole principle of construction trustworthy. No noticeable relative movements are obtained as a result of differences in the coefficients of expansion between the different parts of the stator and the winding.

According to an advantageous embodiment, the winding is installed, during assembly of the machine, in the slots of the stator with play, which essentially corresponds to the expected expansion of the winding during the operating temperature of the machine. The winding, before installation in the slots of the stator, can alternatively be deformed mechanically in such a way that the winding, which is installed thereafter in the slots, returns to its non-deformed state and bears on the walls of the slot. According to another alternative, the winding may be cooled down before installation in the slots of the stator, undergoing thereby thermal shrinkage, after which the winding is installed in the slots and regains its original state as a result of heating whereby the winding bears on the walls of the slot. In all cases the stator is heated, after the winding has been installed but before operating, with advantage to a temperature T3, which preferably essentially corresponds to the expected operating temperature T0.

Thus, the system for supervision of the machine comprises with advantage also means for measuring the temperature of the stator before being taken into operation for the first time, means controlling the cooling and heating system such that the stator, before operating for the first time, is heated to a temperature T3, and means which control the machine such that it is taken into operation only when the temperature T3 has been reached.

The temperature T3 may even be somewhat lower than the expected operating temperature of the stator T0, whereby T3 is preferably in the range of 0 - 20^0C lower than T0, and with advantage in the range of 0 - 10^0C lower than T0.

The advantage of having a winding which is not fastened within the slot of the stator until the operating temperature has essentially been reached is obtained by utilising, among other things, the "memory effect" of an XLPE-insulated conduc-

tor or similar conductor which is released by heat or time. This also improves the possibilities of replacing a damaged part of the winding.

According to an preferred embodiment, the cooling and heating system of the rotating machine comprises at least one expandable conducting means for transportation of a cooling and/or a heating medium, which is inserted into ducts in the stator core, which are adapted for this purpose, in addition to means for the expansion of said conducting means, whereby said conducting means after having expanded, presses against the inside of the duct in order to obtain good contact and heat transfer.

Said conducting means, which is preferably a proportionately rigid tube made of XLPE material or the like, has with advantage, before being inserted, been coated with a layer of fusible adhesive, in the form of glue film for example, which is wound onto the tube or extruded on the outside of the tube. The thickness of the layer may be in the range of one to some tenths of a mm. The fusible adhesive may contain a filler having good thermal conductivity such as aluminium oxide or boron nitride.

Additionally, the machine comprises with advantage means for the expansion of the conducting means, comprising means for simultaneously subjecting the conducting means to overpressure and heating, so that the conducting means bears on the walls of the duct and so that said fusible adhesive melts and substantially fills all cavities between the conducting means and the walls of the duct, whereby the conducting means is secured against the walls of the duct. Pressurisation and heating can take place by, for example, warm glycol being circulated inside the conducting means. Heating up to approx. 150^0 is required for the XLPE material and the conducting means to expand, and the medium used for pressurisation and heating must therefore be able to withstand this temperature. Besides, the medium can consist of the cooling and /or heating medium, which is used later for cooling and heating the stator respectively. The conducting means becomes supple and can be reshaped during heating and the glue, which melts and fills up possible cavities between the conducting means and the stator core, then hardens and secures the conducting means when cooling down. This arrangement has the advantage of being able to substitute the injection of silicon rubber, which is otherwise used for securing the conducting means and as a "sealing" between the conducting means and the stator ducts. The invention therefore shortens the distance

that the heat travels between the stator core and the conducting means by approx. 2 mm.

According to a variant, the conducting means can be deformed radially, before being inserted into the duct, so as to correspond to a smaller diameter than that of the duct.

According to another preferred embodiment, the cooling and heating system of the rotating machine comprises at least one expandable conducting means for transportation of a cooling and/or a heating medium, which conducting means is inserted into the slots of the stator core, in the cavities that are formed between the turns of the winding lying adjacent to each other, in addition to means for the expansion of said conducting means, whereby said conducting means, after having expanded, clamps the winding firmly within the stator slots. This conducting means has with advantage a profile, which principally corresponds to the geometrical cross-section of said cavities and which is preferably an essentially triangular profile.

According to a variant, the expandable conducting means is inserted into the slots of the stator core in an evacuated condition. The conducting means may, for example, be made of reinforced hose and said means for the expansion of the conducting means, being inserted into the slots of the stator core, preferably comprise means for feeding a pressurised fluid into the conducting means. The conducting means can, for example, be pressurised by means of a static water pressure, whereby the winding is clamped firmly within the stator slot. The water can be circulated thereafter in order to heat and cool the slot/stator and winding respectively.

According to another variant, said means for the expansion of the conducting means comprise means for simultaneously subjecting the conducting means to overpressure and heating, and the machine also comprises means for cooling the conducting means while retaining an overpressure, whereby the conducting means retains its expanded form. The conducting means then preferably constitutes an XLPE-tube or is made of a similar material, which can be made to expand in a corresponding manner to the above-mentioned description of the conducting means within the ducts of the stator core, and which has the corresponding advantages.

Additional features and advantages of the present invention will be made evident in the remaining dependent claims.

Thus, not only has a solution been found for the problem of avoiding temperature changes in the stator and other problems in this connection, improved ways and devices have also been found for securing the winding in the stator slots and fastening the conducting means for heating and cooling purposes within the ducts in the stator core and the slots, in addition to finding a solution for improved heat transmission.

Embodiments of the present invention will now be described, by way of example only, with particular reference to the accompanying drawings in which:

Figure 1 shows a schematic sketch of the supervision system, which is part of the invention;

Figure 2 shows a schematic sketch illustrating the installation of the winding in the stator slots;

Figure 3 shows a variant of the installation of the winding;

Figure 4 shows ducts in the stator core, into which a conducting means for transportation of a cooling and/or heating medium has been inserted;

Figure 5 shows stator slots with winding and conducting means for transportation of the cooling and/or heating medium; and

Figure 6 shows an example of an insulated electric conductor suitable for use as winding.

Figure 1 shows schematically, in accordance with the invention, the specifications that a supervision system for a rotating electric machine will perform. As mentioned above, it is desirable that the temperature of the stator, when it has been put into operation, remains relatively constant. In order to achieve this, a system cooling the stator in operation and heating the stator when it is out of operation is required as well as a supervision system. Examples of different embodiments constituting cooling and heating systems will be shown below, not excluding other possible embodiments. Measurement of the temperature of the stator is an important part of the supervision system. The supervision system can naturally also be used to control the temperature that the conducting means for cooling and heating the stator and winding respectively are heated up to and cooled down to respectively during installation, as well as controlling the pressure they are subjected to, or anything else that is serviceable in this connection. The supervision

system and controlling system inclusively, for the cooling and heating system and the measurement of the temperature of the stator are preferably computerised. Such a system can be designed with the help of known technique and will therefore not be described in detail herewith.

As in the above-mentioned, it is especially desirable to use a type of insulated electric conductor or cable, which is a so-called XLPE-cable, as winding which in the present connection is also termed an XLPE-insulated conductor. This cable expands when the temperature rises, i. e. when the machine is in operation and this condition can be exploited during installation of the cable. As illustrated in Figure 2, on the right hand side of the illustration, the cable 8 is installed in the stator slots with play between the outside of the cable and the inside of the slot. When the stator is heating up, which must take place before it is put into operation because the winding, shown on the right hand side of Figure 2, has not been fastened in the slots yet, the cable expands thermally so that it bears on the slot and is thus secured in the slot. The machine is then ready for service. The purpose of the supervision system is to control the temperature of the stator so that it reaches a temperature that approximately corresponds to the operating temperature, of which temperature the cable is presumed to be secured in the slot, before the machine starts operating. A stator slot 9' is illustrated on the left-hand side of Figure 2 where the winding/cable 8' has expanded to such an extent that it is secured adjacent to the inner wall of the slot and the machine is then ready for service.

Alternatively, the "memory effect" of the cable can be utilised in order to cool down the cable before installation in the slot. When the cable is heated the cable regains its original dimension and then bears on the walls of the slot and the iron core.

It should be noted that it is important that, when the operating temperature has been reached, it be kept at a fairly constant level, i. e. when the machine is out of operation, a temperature is maintained, which is approximately equal to the operating temperature derived from heating, so that the winding will not loosen its adjacent hold on the inside of the stator slots as a result of shrinkage when cooling down too much.

The variant illustrated in figure 3, for installation of the winding, shows a stator having especially designed slots 19 for the winding, i.e. slots, which are oval in the radial direction. Two electric conductors 18 are installed in each such oval

slot 19, i.e. corresponding to two winding turns. Thus, the conductors of the winding can be wound two at a time. This variant is especially advantageous for air-cooling but can naturally also be used in other types of cooling. More space is usually needed in the slots in order to utilise air-cooling and by winding the conductors of the winding two at a time, in the oval slots, a duct shaped space is formed between the two conductors in a slot, which duct may be utilised for cooling. Thus, this invention makes it possible to cool both the winding and the stator teeth by means of air.

The conductors 18 may suitably be treated and installed in accordance with the method described above, in connection with figure 2. Alternatively or complementary thereto, combined means 17, which are of a corresponding type and can be arranged in a corresponding way to the above, may be applied between the two conductors 18 in a slot 19 in order to clamp the conductors and which means can be utilised for cooling/heating the stator and the winding, which will be described further below.

It should be noted that the invention illustrated in figure 3 can also constitute a separate invention as regards a stator having oval slots in which the conductors of the winding are installed two at a time, which invention is not solely confined to a rotating electric machine of the type referred to in claim 26 or to the method defined in claim 1. It should also be noted that the means 17 could be constituted of winding clamping means of any suitable type, i. e. without the combined cooling and/or heating function.

Figure 4 shows how the cooling/heating of the stator may be carried out. The stator core 20 is provided with a plurality of ducts 21 for cooling/heating. A conducting means 22 is inserted into these ducts in order to transport a cooling and/or heating medium, which conducting means preferably constitutes an XLPE-tube or the like. The tube has preferably been deformed radially in advance so that it corresponds to a diameter that is smaller than the diameter of the duct in the stator steel sheets. In any case, the tube 22 has a diameter of d_1, which is smaller than the diameter of the duct d_k. This considerably simplifies the process of leading the tube into the duct. The tube 22 is then allowed to expand in the duct until it attains a diameter d_2 which preferably corresponds to or is somewhat bigger than the smallest diameter d_k of the duct in order to ensure that the conducting means/-tube is secured and bears on the inside of the duct, and thereby to the stator steel

sheets, in such a way that it obtains good contact and good heat transfer. The expansion of the tube is preferably achieved through a combination of heating and pressure, caused by a heated, compressed fluid circulating through the conducting means.

The conducting means/tube can be coated on its outside with a layer of fusible glue film, which melts when the tube is heated in order to further improve the process of fastening the conducting means so that it bears on the inside of the duct. The glue then fills all possible cavities between the conducting means and the stator sheet layers in the core duct. The glue film can also contain a filler having good thermal conductivity such as aluminium oxide or boron nitride, which further improves the melting of the glue and the contact of the conducting means to the stator sheets as well as the heat transfer between the conducting means and the stator.

Figure 5 shows how a conducting means 27 for transportation of a cooling and/or heating medium can be located in the space between the winding 28 and the stator slot 29. This conducting means can have the same characteristics as the conducting means, being used in the ducts in the stator core. Thus, this conducting means can be constituted of an XLPE-tube which has advantageously been given a triangular profile, which corresponds to the form of the accessible space between the inside of the stator slot and two winding turns 28 lying adjacent to each other. This could have taken place through deforming the conducting means. The conducting means can expand in a corresponding way to the abovementioned after having been inserted, i. e preferably by means of a combination of heating and pressurising a medium circulating through the conducting means. Thus, the conducting means hereby bears on both the insides of the slot and the winding whereby the conducting means thus fixes the winding within the stator slot. Good contact is established at the same time between the conducting means and the winding as well as the stator sheets, which is favourable for heat transfer and can thus be utilised for cooling and heating of the stator (and the winding) respectively. The conducting means in this figure 5 is only arranged on the one side of the winding but can naturally be arranged on both sides of the winding, such as shown previously in figure 3. It is also noteworthy that figure 3 illustrates a corresponding conducting means in a non-expanded condition.

A reinforced hose can alternatively also be used as a conducting means instead of the XLPE-tube, which is preferably threaded in an evacuated condition into the accessible spaces. This is thereafter pressurised by means of static water pressure and clamps the winding cable in this manner within the slot.

Finally, a cross-section of an insulated electric conductor/cable is shown in figure 6, which is especially suitable for use as winding in the stator according to the invention. The cable 30 comprises at least one current carrying conductor 31 surrounded by a first semiconductive layer 32. An insulation layer 33 is arranged around this first semiconductive layer, which layer is surrounded in turn by a second semiconductive layer 34. The electric conductor 31 can consist of a plurality of strands 35. The three layers are designed in such a way that they adhere to each other even when the cable is bent. The flexibility of the shown cable is a life-long characteristic. The illustrated cable also differs from conventional high voltage cables because the outer, mechanical protective sheathing and the metal screen, which normally surrounds such a cable, are eliminated.

The present invention should not be considered limited to the shown embodiments, but can be varied by a person skilled in the art in numerous ways within the frame of the invention as defined in the attached patent claims.